Magnetic Properties of Perminvar[1]

By G. W. ELMEN

SYNOPSIS: This paper describes the magnetic properties of a group of iron-nickel-cobalt alloys, named "perminvar." With certain heat treatments these alloys have unusual constancy of permeability and extremely small hysteresis losses at low flux densities, and peculiarly shaped hysteresis loops constricted in the middle as the maximum flux densities of the loops are increased. Methods of preparing and heat treating the alloys are described, limits of composition, and changes in the magnetic properties with composition and with different heat treatments are illustrated. A theory of constitutional changes effected by heat treatment and responsible for the unusual magnetic properties is suggested.

IN 1921 the writer was investigating the magnetic properties of a series of permalloys[2] to which a few per cent of a third metal was added to the nickel and iron. One of these alloys contained cobalt. Magnetic measurements indicated that up to moderate field strengths the permeability of this nickel-cobalt-iron alloy was remarkably constant. The constancy was materially better than for soft iron, notwithstanding the fact that the initial permeability was several times higher. This was unusual, as small permeability variation ordinarily is found only in materials with low permeability. Measurements of other magnetic properties were equally surprising. When the hysteresis loop was traced for a cycle which carried the flux density up to a few thousand gauss, it was found to have an extraordinary form in that it was sharply constricted in the middle. These and other differences which were observed indicated that this alloy was a new type of magnetic material in which the magnetic properties were fundamentally different from those of previously known materials.

This discovery aroused a great deal of interest for it was recognized that magnetic materials possessing these properties were of great scientific and technical importance. In order to develop the possibilities which this alloy suggested, an exploration of the whole field of the iron-nickel-cobalt series was undertaken. For it was, of course, apparent that the alloy which had aroused our interest must be one of a group of compositions which possessed similar properties in a greater or less degree. In this survey, alloys varying in 10 per cent steps in composition and including the whole range of the ternary

[1] Reprinted from *The Journal of the Franklin Institute*, Vol. 206, No. 3, September, 1928.
[2] Arnold & Elmen, *Jour. of Frank. Inst.*, May, 1923, p. 621.

series of these metals were made up and their magnetic properties measured.

These measurements showed the range of compositions which shared in such unusual magnetic properties, and indicated that heat treatment was an important factor in the development of these properties. A large number of alloys have been made up in this range, for which the variations in composition were evenly distributed but much smaller than for the initial survey. From these alloys a few were selected which appeared to be specially suited for magnetic uses in electrical communication circuits. Our experience with these alloys has been that when good grades of commercial materials are used, the castings are readily reduced mechanically to the desired dimensions, and the magnetic properties from different castings of the same composition are quite uniform.

We felt that these alloys were so unique as regards magnetic quality that they should be grouped in a class under a common name which should readily distinguish them from other materials. We have chosen "perminvar" as the name for alloys in the iron-cobalt-nickel series, which are characterized, when properly heat treated, by constancy of permeability for a considerable range of the lower part of the magnetization curve, by small hysteresis loss throughout the same range of flux densities, and by a hysteresis loop constricted at the origin for medium flux densities.

This paper describes the magnetic properties of the perminvar group of alloys. Results are given for several alloys selected to show the variation in magnetic properties when the proportions of the constituent metals are varied over a wide range. Detailed measurements under a variety of magnetic conditions and heat treatments are recorded for the composition 45 per cent nickel, 25 per cent cobalt and 30 per cent iron. This composition is a typical one and was chosen early in our experimental work as specially suitable for commercial uses, for it had, in addition to the unusual properties in which we were most interested, a fairly high initial permeability.

Preparation of Alloys

The alloys were cast from the best available commercial materials. Armco iron, electrolytic nickel and commercial cobalt were melted together in the desired proportions in a silica crucible in a high frequency induction furnace. Before pouring, one half of one per cent of metallic manganese was added to the molten metal. Part of this manganese deoxidized the metal and went into the slag, and the remainder, usually about one half of the added amount, remained in

the alloy. The alloys also contained small amounts of carbon (less than .03 per cent), silicon (less than .1 per cent) and traces of sulphur and phosphorus. The alloys were cast into bars 18 in. long and 3/4 in. in diameter. The bars were rolled or swedged into 1/4 in. rods and drawn from that size to .062 in. diameter wire. This wire was flattened and trimmed into tape 1/8 in. × .006 in. The material was annealed several times in the reduction process, for the cold working hardened the alloys rapidly and made them difficult to work.

To prepare the tape for heat treatment and subsequent magnetic measurements, about 30 ft. of it was wound spirally into a ring of 3 in. inside diameter, the ends being spot welded to the adjacent turns. Care was taken to wind the rings loosely to prevent the turns of tape from sticking during annealing.

A number of such rings were packed in a nichrome pot. Some iron dust was usually placed in the pot to take up the oxygen and thus prevent the oxidation of the rings. Further protection was secured by luting the joint between the pot and its cover. The pot was placed in an electrical resistance furnace, the temperature of the furnace raised to 1000° C. and held at that temperature for one hour. The current was then turned off and the pot cooled with the furnace. Ten hours were required for the furnace to cool to the temperature of the room. Between 700° C. and 400° C. the rate of cooling was approximately 1.5° per minute.

Three rings of each composition were always annealed together. One of these rings received no further heat treatment. The second ring was placed for 15 minutes in a furnace held at 600° C., then removed and cooled rapidly on a copper plate. In some cases, the third ring was heated 24 hours at 425° C.

In the discussions and in the figures and tables, the rings which received the first heat treatment only are referred to as "annealed," those reheated to 600° C. and rapidly cooled as "air quenched," and those held for a long time at 425° C. as "baked."

Magnetic Measurements

Permeabilities at low magnetizing forces were measured on unwound rings with an inductance bridge, and an a.c. permeameter.[3] From these measurements initial permeabilities were computed. For elevated temperature, measurements were made with a similar permeameter provided with a furnace compartment.[4] The bridge was also used for measuring permeabilities to small a.c. magnetizing forces when d.c. forces are superposed on the magnetic circuit. For these

[3] G. A. Kelsall, *J. O. S. A.* and *R. S. I.*, **8**, pp. 329–338, 1924.
[4] G. A. Kelsall, *J. O. S. A.* and *R. S. I.*, **8**, pp. 669–674, 1924.

measurements the rings were wound with insulated copper wire after being placed in thin annular wooden boxes to protect them from strain. Hysteresis losses were computed for a few alloys from effective resistance measurements at low flux densities, made on wound rings.

Magnetization and permeability curves and hysteresis loops were plotted from ballistic galvanometer measurements. Galvanometer measurements also were made on a few alloy rods 11 in. long and 1/8 in. diameter, at a magnetizing force of 1500 gauss. For these measurements the rods were placed in a long solenoid and the induction measured by means of an exploring coil at the center of the rod.

Properties of the 45 Per Cent Ni, 25 Per Cent Co, 30 Per Cent Fe, Composition

Measurements for the composition 45 per cent nickel, 25 per cent cobalt and 30 per cent iron in the annealed condition are plotted in Figs. 1–7 and tabulated in Table I. The curves in Fig. 1 illustrate the permeability characteristics for this composition (No. 858–1) and for a sample of annealed Armco iron. For magnetizing forces below 1.7 gauss, the permeability is substantially constant, the variation being less than 1 per cent. This constancy is remarkable for a magnetic material having an initial permeability nearly double that of iron. Within the same range of field strengths the permeability of the iron sample rises from an initial value of 250 through a maximum of 7,000 at a magnetizing force of 1.3 gauss and decreases to 6,300.

TABLE I.

Hysteresis Loss with Different Heat Treatments for [45% Ni—25% Co—30% Fe] Composition Perminvar

Heat Treatment	B	Ergs per Cm.^{3} per Cycle
Air Quenched	568	18.7
	722	32
	993	57
	1,503	119
	5,010	850
	14,810	2,500
Baked at 425° C. for 24 Hours	600	0
	795	0
	1,003	15.27
	1,604	163
	4,950	1,736
	13,810	4,430
Annealed	570	0
	820	9.54
	974	15.65
	1,508	93.20
	5,050	1,185
	8,480	2,500
	14,900	3,375

Another property of the perminvar alloy closely related to the constancy of permeability is the extremely small hysteresis loss in the range of magnetizing forces and flux densities in which the permeability is constant. This is illustrated in Fig. 2 where line *a* represents the plot of the upper half of the hysteresis loop for a maximum flux

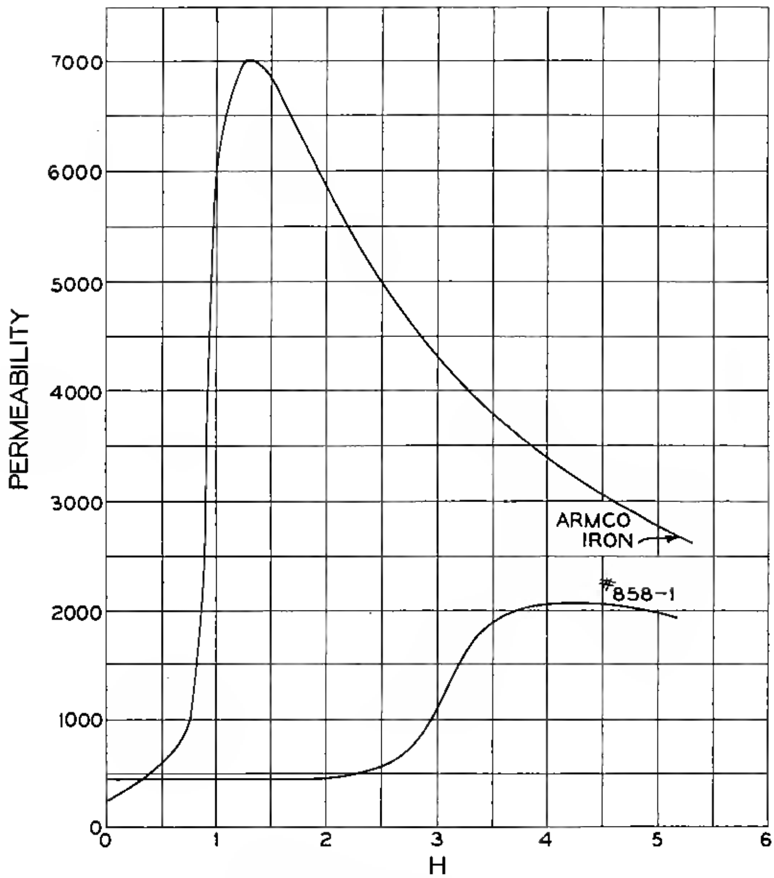

FIG. 1—Permeability curves for Armco iron and Perminvar (45% Ni—25% Co—30% Fe)

density of approximately 600 gauss. Curves *b* and *c* are similar plots for silicon steel ($3\frac{1}{2}$ per cent silicon) and Armco iron respectively. While the hysteresis loops for Armco iron and silicon steel have considerable areas amounting to 33 and 14 ergs per cubic centimeter per cycle respectively, there is no measurable area for the perminvar alloy. Although the ballistic method of measurements which was

used in obtaining these curves, does not indicate very small losses readily it is evident that the losses in the perminvar alloy are of a different order of magnitude from those of the other two materials. In order to obtain additional information in regard to the hysteresis loss of this alloy at low flux densities, the sample was measured by the inductance bridge method. It was found that the hysteresis loss at a flux density of 100 gauss was $.024 \times 10^{-3}$ ergs per cubic centimeter per cycle. The best material in this regard previously known was permalloy, for which a sample containing approximately $78\frac{1}{2}$ per cent nickel, measured under similar conditions, had a hysteresis loss of 33×10^{-3} ergs per cubic centimeter per cycle.

The growth of the hysteresis loss and the appearance of measurable areas, and the peculiar shapes of the loops for this composition as the flux densities increase are illustrated in Fig. 3. The curve for a

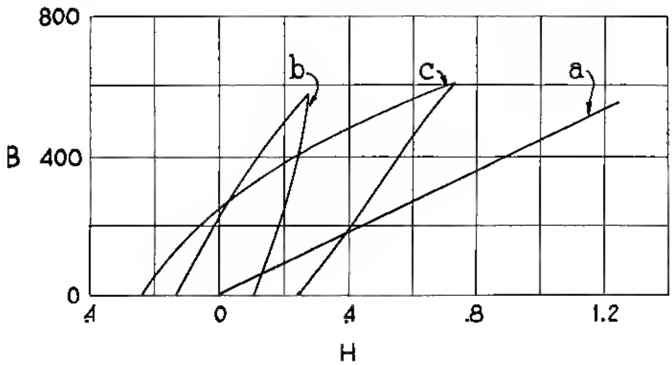

Fig. 2—Hysteresis characteristics: *a*—Perminvar (45% Ni—25% Co—30% Fe); *b*—silicon steel; *c*—Armco iron

maximum flux density of 580 gauss in Fig. 3, is from the same data as Curve *a* in Fig. 2. The circles in this plot indicate points on the ascending branch, and the dots, points on the descending branch. The hysteresis loop broadens out so that it has a measurable area when the maximum flux density is increased to 800 gauss. The existence of a close relation between the hysteresis losses and the constancy of permeability is quite apparent from the permeability curve in Fig. 1 and the curves in Fig. 3. While the permeability remains constant there is practically no hysteresis loss but as it begins to change this loss appears and increases quite rapidly with increase in permeability. The increase in the energy loss and the changes in the shapes of the loops as the flux density increases also are illustrated by these curves. The most striking hysteresis characteristic of these

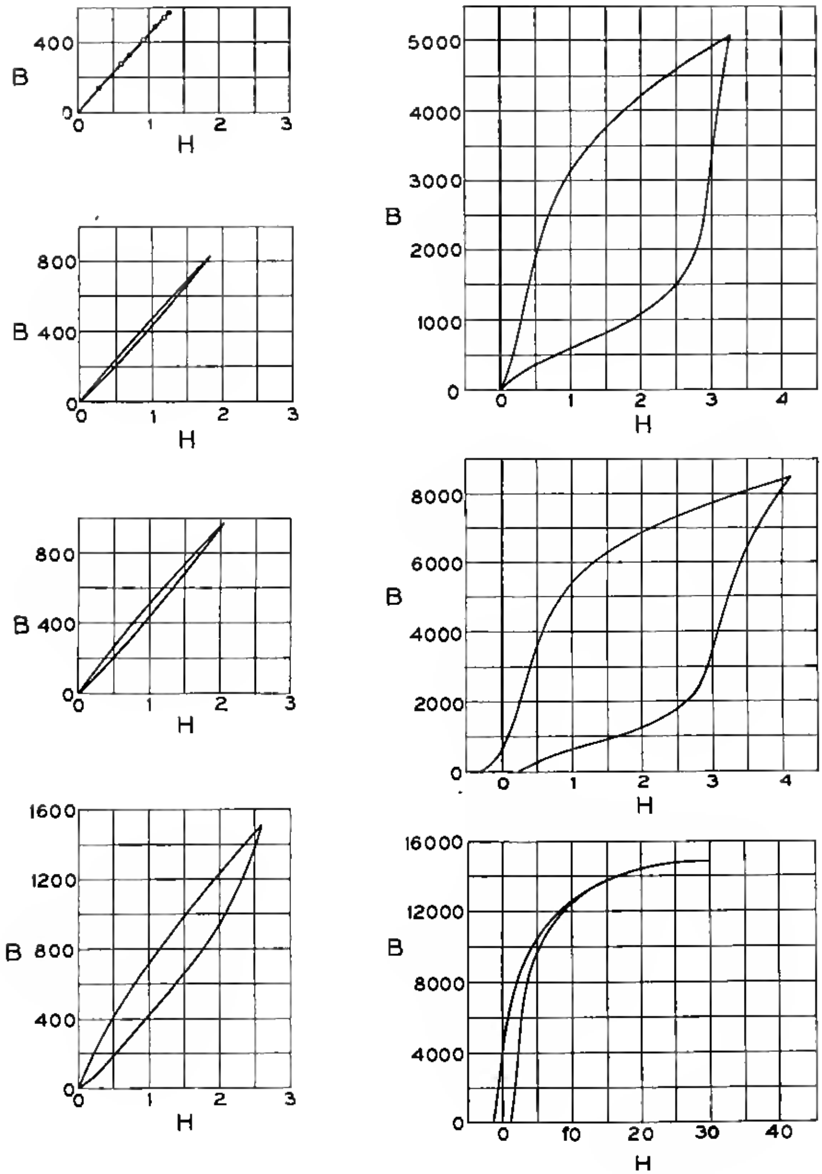

FIG. 3—Upper halves of hysteresis loops of Perminvar (45% Ni—25% Co—30% Fe) annealed

loops is the absence of coercivity. For loops having maximum flux densities of 5,000 or less the ascending and descending branches pass through the origin. For greater flux densities the coercivity begins to be measurable, but there is still a considerable constriction of the loop for a maximum flux density of 8,000 gauss. It is only in the loop for 15,000 gauss, that the constriction at the origin has disappeared and the loop resembles those for ordinary magnetic materials. In Table I the hysteresis losses for the complete loops are tabulated.

Fig. 4 illustrates graphically how the permeability measured with a constant alternating current magnetizing force of about .0021 gauss and 200 cycles per second is affected when a steady magnetizing force

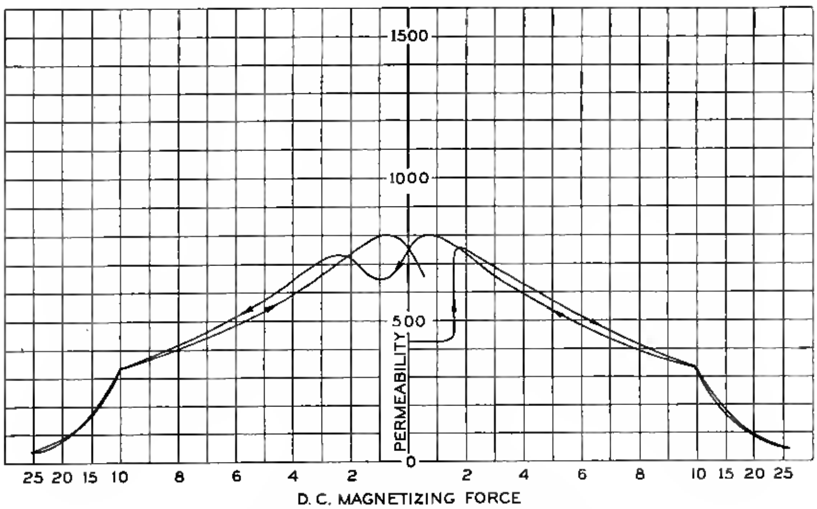

Fig. 4—The effect of superposed d.c. fields on the a.c. permeability of Perminvars (45% Ni—25% Co—30% Fe)

is superposed on the magnetic circuit, the steady force being produced by a direct current. The arrows in the figure indicate the direction in the progress of the permeability as the direct current magnetizing force is varied. The permeability is substantially constant as the direct current magnetizing force increases up to approximately 1.7 gauss and it then suddenly rises as the force is increased beyond that value. This is the same field strength at which the permeability begins to increase as shown in Fig. 1.

Another characteristic of this material not found in ordinary magnetic substances also is shown in Fig. 4. After an applied d.c. magnetizing force of 25 gauss is removed, the permeability has risen from 460 to 750. With ordinary materials, after such magnetization,

the permeability is reduced, in some cases from 40 to 60 per cent. With the increase in permeability its constancy disappears both for the superposed condition as shown in Fig. 4, and for ordinary magnetizations at low field strengths. The hysteresis losses are also increased for corresponding flux densities. These changes in the

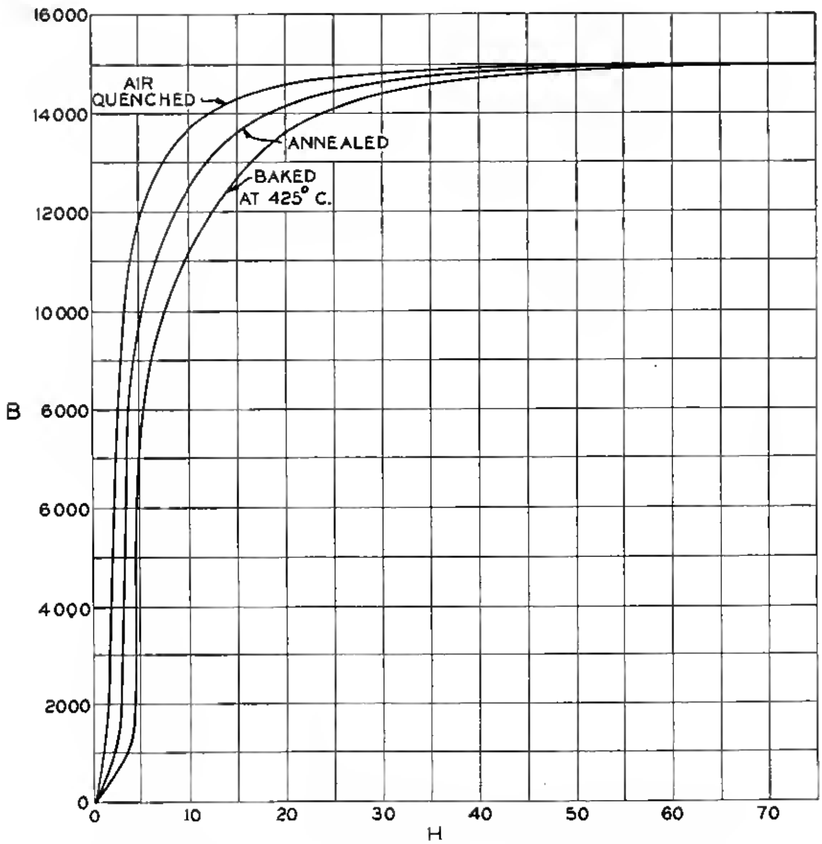

Fig. 5—Magnetization curves for Perminvar (45% Ni—25% Co—30% Fe)

magnetic properties are largely removed by demagnetization. The ordinary method of demagnetization by reversals of a slowly decreasing magnetizing force has been less successful than it is with iron in returning the material to its initial state. Addition of an a.c. force superposed on the d.c. helps materially in restoring the original magnetic properties.

Effects of Heat Treatment

The manner in which the magnetic properties of this composition are affected by the rate of cooling is illustrated in Figs. 5–7. The measurements plotted in these figures are from three rings, air quenched, annealed and baked, respectively. For weak fields there are large differences in the magnetic properties for these rings. The initial permeability for the quenched ring is more than twice that of the baked one. With increased field strength this difference decreases and disappears for fields over 50 gauss. The permeability variations as the strength of the field increases also show the remarkable change

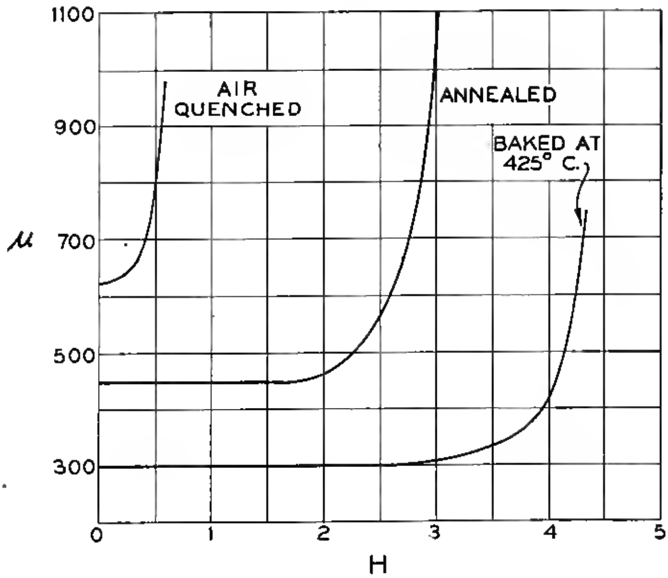

Fig. 6—Permeability curves for Perminvar (45% Ni—25% Co—30% Fe)

which heating for a long time in the critical temperature range produced in these alloys. For the quenched ring the permeability increased from 620 to 800 for an increase of field strength from 0 to .5 gauss. For the baked ring the permeability remains constant for fields up to 2.5 gauss.

The hysteresis loss and the shapes of the loops also are affected greatly by the heat treatment. This is illustrated in Fig. 7, where loops for a number of flux densities are plotted for two sample rings, one baked at 425° C. and the other air quenched, and in Fig. 3 where loops for the same maximum flux densities are plotted for an annealed

ring. The energy losses integrated for complete loops are tabulated in Table I.

These curves show that the rate of cooling determines the magni-

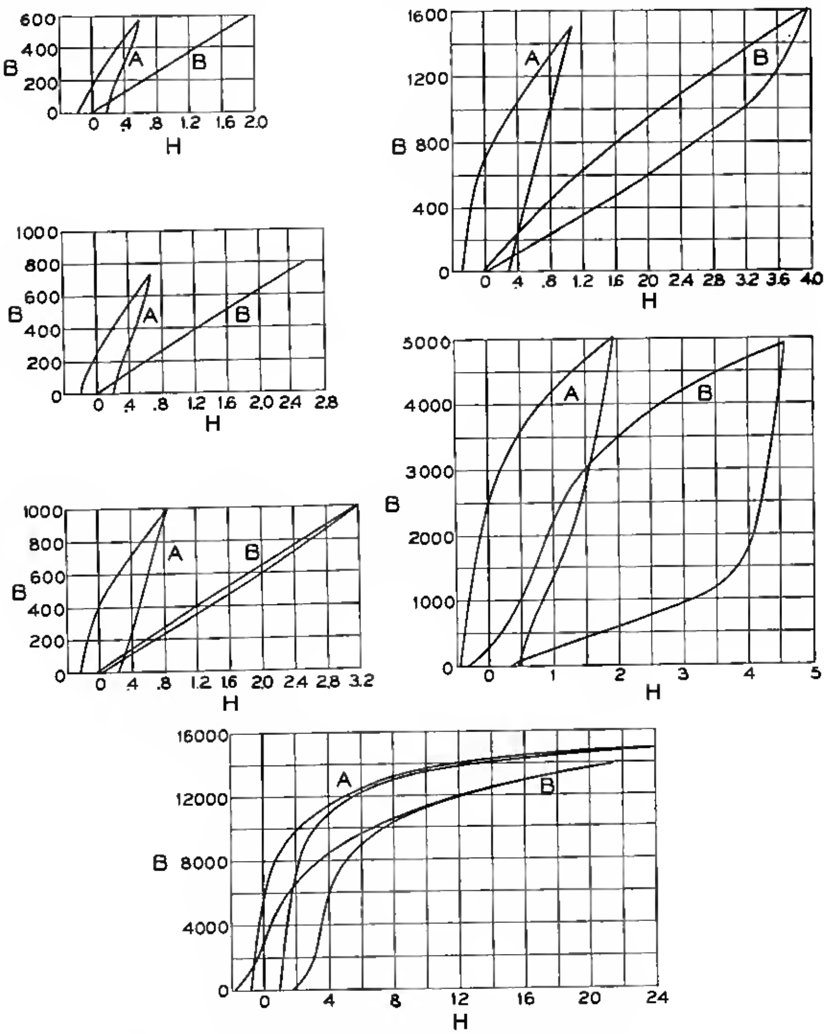

FIG. 7—Upper halves of hysteresis loops for Perminvar (45% Ni—25% Co—30% Fe) *A*—air quenched, *B*—baked at 425° C.

tudes of the hysteresis losses and the shapes of the hysteresis loops. For the air quenched rings the shapes of the loops for the different flux densities resemble those for ordinary magnetic materials although a few of them show traces of the perminvar characteristics. If a

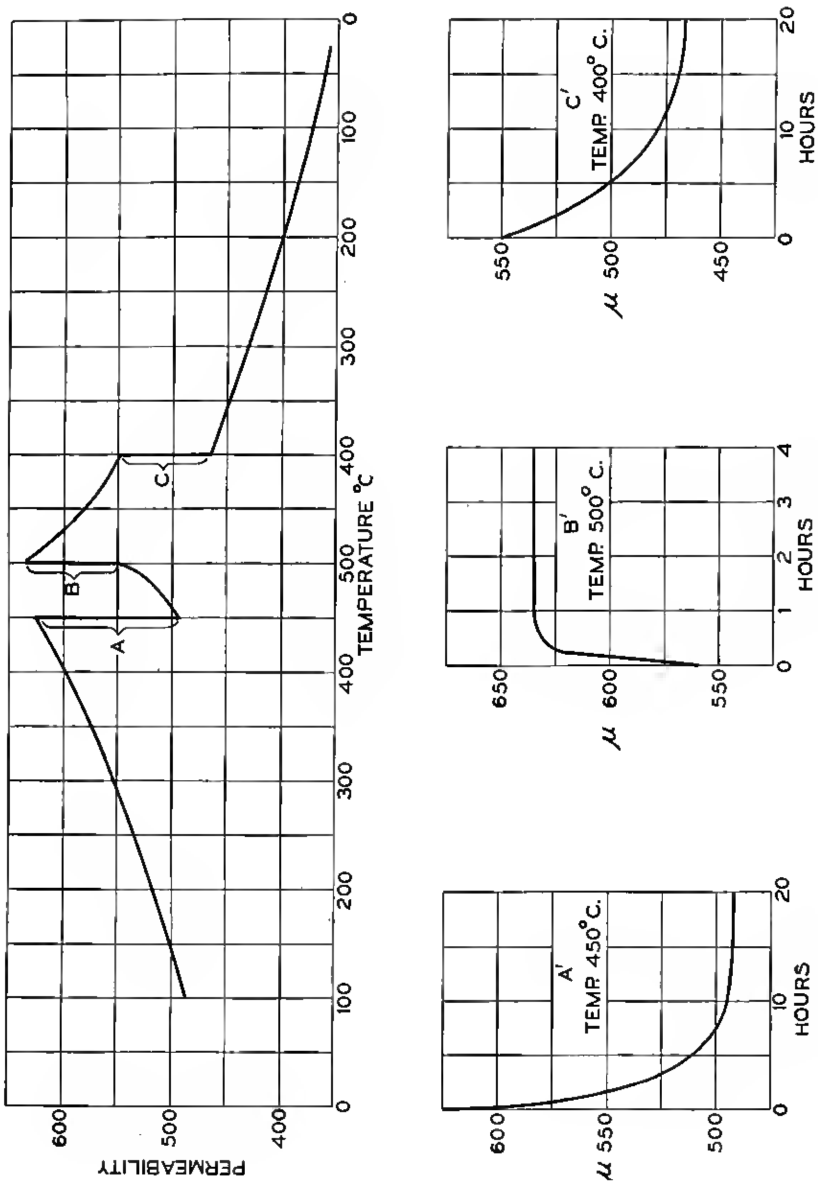

FIG. 8—Permeability—Temperature curve for Perminvar (45% Ni—25% Co—30% Fe)

more rapid cooling rate had been used these characteristics no doubt would have disappeared completely. The hysteresis loops all have considerable areas. The one for 568 gauss, the lowest flux density measured, represents an energy loss of 18.7 ergs per centimeter cube. For the same flux density, the hysteresis loops for the annealed and the baked rings have no measurable areas, the ascending and descending branches of the loops falling on the straight lines shown in

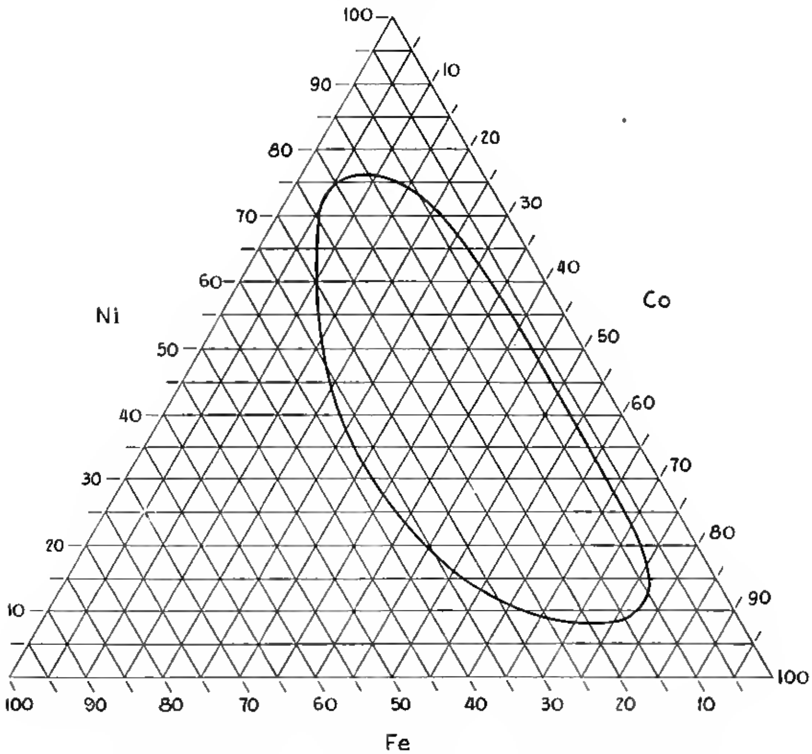

FIG. 9—Composition diagram Ni—Fe—Co Series. Area enclosed by the curve shows compositions with marked Perminvar characteristics

the figure. This absence of measurable area extends up to a flux density of nearly 1,000 gauss for the baked ring. The increase of energy loss as the flux density increases above this value, however, is considerably more rapid than for the quenched ring. At 1,500 gauss, the hysteresis loss is a little greater than for the quenched ring and when the flux density is increased to 5,000 gauss, the loss is more than double.

It was shown above that the degree to which perminvar charac-

teristics are developed depends on the rate of cooling through the critical temperature range, and that baking at 425° C. gave the most characteristic results. The manner in which the permeability of the 45 per cent nickel, 25 per cent cobalt and 30 per cent iron composition changes in this temperature range is illustrated in Fig. 8. The temperature of an annealed ring was increased from that of the room to 450° C. where it was held constant for twenty hours. It was then raised to 500° C. and held for four hours, then lowered to 400° C. where it was held for twenty hours, and finally cooled to room temperature. Permeability measurements were made at these temperatures with an a.c. magnetizing force of .02 gauss.

Inspection of these curves shows that in the range 400°–500° C., the permeability lags behind the temperature, and that the time required for the permeability to reach a constant value increases very rapidly below 450° C. The changes in final permeabilities with temperature decrease also rapidly below 450° C. In fact, when the difference in permeability caused by the temperature coefficient is corrected for, the permeability of the alloy after heating at 400° C. is not very different from what it is after heating at 450° C. Other experiments show that the critical temperature range extends below 400° C., but, as would be expected, the decrease in permeability is very small. The range also extends above 500° C. for this alloy and some experiments indicate that the upper limit is the magnetic transformation temperature which for this alloy is 725° C.

Effects of Variation of Compositions

The composition range within which the magnetic properties characteristic of perminvar are developed pronouncedly by annealing, is represented by the area enclosed by the curve in the triangular composition diagram Fig. 9. Magnetic properties for a few of the compositions in this area are plotted in Figs. 10 and 11. Table 2 gives their chemical analyses, initial permeability (μ_0), the maximum permeability ($\mu_{max.}$), the magnetizing forces (H) and the flux densities (B) in gauss to which the alloys may be brought with a permeability variation not over 1 per cent, also the $(B - H)$ values for a magnetizing force of 1,500 gauss for some of the alloys, and the resistivity in microhms-cm. The hysteresis losses for a number of flux densities are given in Table 3.

The area enclosed in Fig. 9 shows that approximately one third of the alloys in the Ni-Fe-Co series show some of the characteristic perminvar properties in the annealed condition. The proportions of nickel and cobalt may be varied through a wide range. A great deal

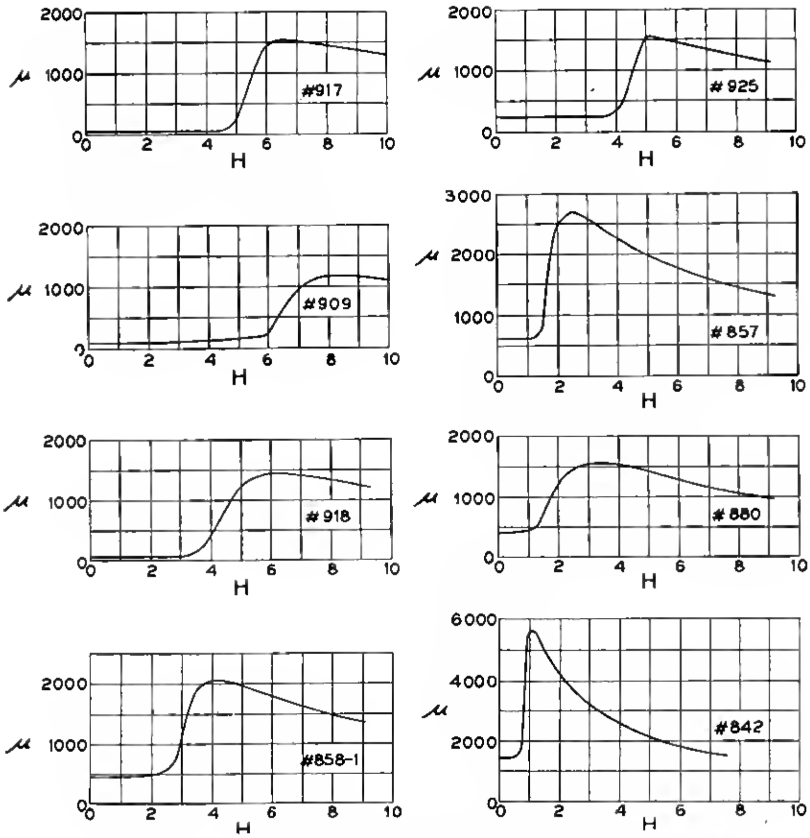

FIG. 10—Permeability curves for several compositions of Perminvar. Chemical analysis given in Table II

TABLE II

CHEMICAL COMPOSITION AND MAGNETIC PROPERTIES OF PERMINVARS

Casting Number	Chem. Analysis				Magnetic Properties					Resistivity
	Ni	Co	Fe	Mn	μ_0	μ_m	H for 1% Ch. in μ	B for 1% Ch. in μ	$B - H$ for $H = 1{,}500$	Microhm-Cm.
917	11.35	68.10	20.36	.35	57	1,545	4.2	242	18,400	15.38
909	20.85	49.18	29.74	.31	98	1,180	4.0	396	18,200	16.59
918	20.73	68.35	10.58	.39	51	1,447	2.5	129	17,400	12.35
858-1	45.12	23.83	30.69	.46	449	2,075	1.75	793	15,600	18.63
925	50.47	29.28	20.15	.33	231	1,555	3.2	746	14,600	14.55
857	59.66	14.76	24.97	.60	631	2,680	1.15	733		17.5
880	70.29	15.23	14.57	Tr.	390	1,570	.55	216		14.13
842	73.29	5.97	20.7	.20	1,430	5,600	.55	795		15.56

less variation in the iron content is permissible, being less than one half of the amounts of the other two constituents. The manner in which each of the metals affects the magnetic properties is not very clearly indicated by the numerical values in the table. Iron and

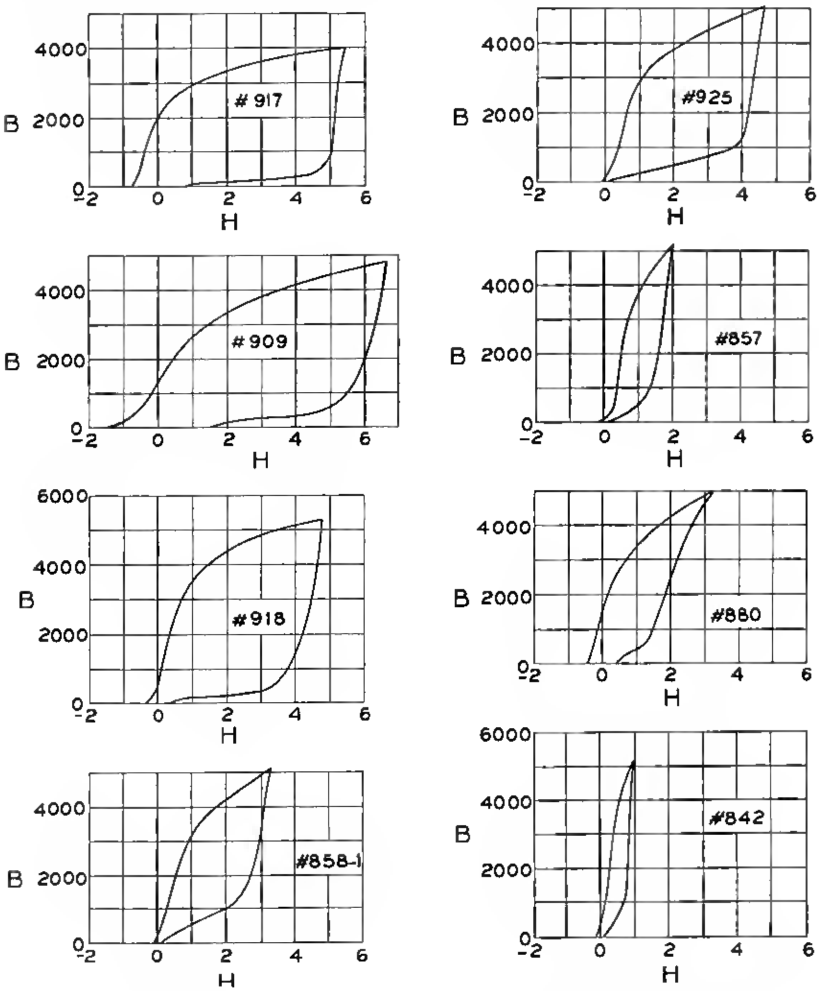

FIG. 11—Upper halves of hysteresis loops for several Perminvar compositions. Chemical analysis is given in Table II

cobalt appear to increase the constancy of the permeability but decrease the initial permeability values. Nickel increases the initial permeability but large percentages decrease the constancy. On the whole, in the alloys with high nickel content, the combination of high

TABLE III

HYSTERESIS LOSS

Casting Number	B	Ergs per Cm.³ per Cycle	B	Ergs per Cm.³ per Cycle	B	Ergs per Cm.³ per Cycle	B	Ergs per Cm.³ per Cycle	B	Ergs per Cm.³ per Cycle
917	280	8	625	150	1,700	1,040	3,950	2,740	15,500	14,160
909	—	—	620	36	1,030	299	4,800	3,330	15,200	12,460
918	—	—	750	247	—	—	5,270	2,605	—	—
858–1	566	0	827	9.5	1,508	93	5,050 8,480	1,185 2,500	14,900	3,375
925	560	0	—	—	2,000	468	5,000	2,020	13,200	4,965
857	145	0	840	8.4	1,520	88	5,200 8,250	632 1,240	13,250	1,508
880	320	0	—	—	1,470	116	5,000	1,012	10,300	2,435
842	500	0	—	—	1,530	23	5,100	348	11,500	783

permeability and fair constancy makes for a larger range of flux densities in which the permeability is constant and consequently also increases the range of flux densities with low hysteresis loss.

Experiments on several alloys of this series indicated that by baking the alloys at 425° C. the area enclosed by the curve in Fig. 8 would be increased considerably, and possibly would include some of the binaries of these metals.

Discussion

While this paper is concerned primarily with the study of the magnetic properties of these alloys and the dependence of these properties on composition and on heat treatment, some of the results are of considerable theoretical interest, as they suggest the manner in which the unusual magnetic properties are acquired by the alloys. It was shown in the heat treating experiments that the unusual magnetic properties resulted from suitable heat treatment of certain compositions. Slow cooling through a rather narrow temperature range, or continuous heating for a long time at the lower end of this range resulted in alloys which had marked perminvar characteristics. Rapid cooling through this temperature range usually did not develop these characteristics. From the measurements at elevated temperatures, Fig. 8, it was shown that in the temperature range from 400° C. to 500° C., the change in the alloys is quite rapid at the higher temperature, but that the rate of stabilization slows up as the temperature decreases. When the alloy is heated and cooled through a temperature cycle in this manner, the permeability changes progressively and at each temperature in the cycle the alloy reaches a stable condition if the rate of cooling or heating is slow enough. There is a striking similarity in the manner in which these changes in permeability are developed, and in the progress of the constitutional changes in an alloy which at high temperatures is a homogeneous solid solution, but as the temperature falls becomes saturated and segregates into a mixture of two solid solutions of different concentration.

That such a segregation takes place in the slowly cooled alloys is also supported by a study of the differences in the shapes of the hysteresis loops of the quenched and the slowly cooled alloys. Ordinarily, the widest part of a hysteresis loop of a homogeneous material is the intercept on the H axis. All the loops of the air-quenched alloys have these characteristics. Gumlich [5] has shown that if a magnetic circuit is made of two materials of different magnetic properties, the loops may assume a variety of shapes, ranging from

[5] E. Gumlich, *Arch. f. Elektrotechnik*, Vol. 9, p. 153, 1920.

that of the homogeneous material to one in which two branches converge at the origin into a single line. This constriction of the hysteresis loop is also illustrated for a parallel bimetallic magnetic circuit in Fig. 12 where loops *a* and *b* are traced for a perminvar core and a bimetallic rod, respectively. The rod was 15 in. long and consisted of a core of .04 in. diameter unannealed piano wire and a .006 in. wall permalloy tube, heat treated to give high permeability, and fitting closely to the wire. Though the magnetic circuit condition for the perminvar core is not the same as for the bi-metallic rod, the similarity of the two loops is marked and supports the theory that the constricted loop of the perminvar core is caused by segregation in the alloy.

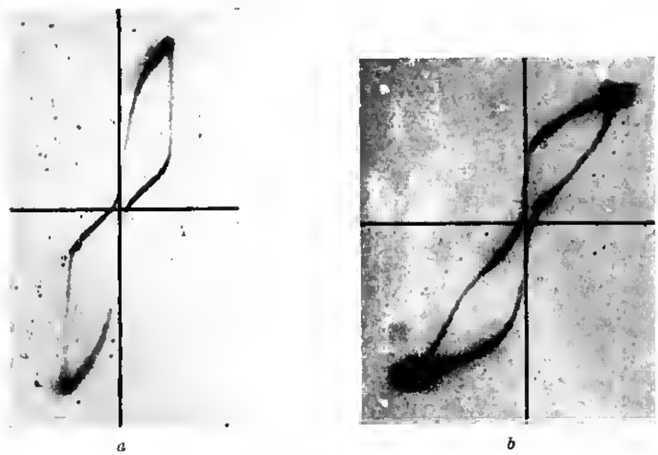

FIG. 12—Hysteresis loops: *a*, Perminvar; *b*, Bi-metallic rod. Loops traced with a cathode ray oscillograph

The electrical resistance also is affected by the slow cooling. An air-quenched alloy of the 45 per cent nickel, 25 per cent cobalt and 30 per cent iron composition was 10 per cent lower in resistivity after it had been baked at 425° C. This change is also in line with the idea that segregation takes place when the perminvar alloys are cooled slowly.

While these considerations point to a satisfactory explanation for the constriction of the hysteresis loops they do not explain the extremely low hysteresis losses of the alloys at low flux densities. This characteristic of perminvar suggests that one of the constituents which is segregated by the heat treatment is itself a material of much lower hysteresis loss than any previously known material and that

the other constituent suffers relatively little change of magnetization at low magnetizing forces.

To the engineer these alloys are of unusual interest. They may be used to advantage for magnetic structures where the magnetizing forces do not exceed the limits of constancy of permeability for the various compositions. Interesting results have been obtained with the 45 per cent nickel, 25 per cent cobalt and 30 per cent iron composition for continuous loading of telephone conductors and for cores of loading and filter coils used in high quality transmission and in carrier current circuits. For such purposes high resistivity is also desired, and it has been found that the addition of a few per cent of other metals such as molybdenum serves for this purpose. For circuits requiring greater constancy or higher permeability other compositions are more suitable. The best alloy for any specific circumstance may be selected from a study of the magnetic properties of the various compositions.